Neutron generation in a vacuum diode with laser-plasma source of deuterons

K.I. Kozlovskij*, E.D. Vovchenko, A.A. Isaev

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe shosse 31, 115409, Moscow, Russia

Abstract

The generation of neutrons in a coaxial vacuum diode with laser-plasma source of deuteron on anode and outer hollow cylindrical cathode is investigated. The experiments were carried out at accelerating voltages in the diode gap of $U_a \leq 280$ kV for two configurations of the electrode system: the cathode made from magnetic NdFeB compound material, providing suppression of electrons stray currents in the accelerating gap, and an aluminum A1 cathode. For the magnetic field inductance on the axis of the NdFeB cathode about $B \approx 0.4$ on the D(d, n)$^3$He reaction the maximum neutron output in the total solid angle $Q = 5 \times 10^7$ neutrons per pulse was received. The absence of magnetic insulation reduced the accelerating voltage on the diode gap and the neutrons output.

Keywords: plasma; diode; deuterons; neutron generation; magnetic insulation.

1. Introduction

The small-sized pulse neutron generators (PNG) on the base of vacuum and gas-filled accelerating diodes are successfully used for neutron logging of oil & gas and ore wells, neutron activation analysis, inspection technologies.

* Corresponding author.

E-mail address: cozlowskij2013@yandex.ru (K.I. Kozlovskij)
for detection and hidden dangerous objects and substances identification [Barmakov (2013)]. The increasing of energetic neutron generation efficiency is of interest, because product dimensions define the possibility of PNG using in a number of applied neutron physics tasks.

Different methods of suppression of secondary electron emission from cathode [Bogdanovich et al. (2009), Didenko et al. (2014)] are widely used in vacuum diodes in order to rise efficient neutron generation. One of the most effective methods is magnetic isolation of electrons in diode gap. Typically, the isolating magnetic field is formed with the help of a solenoid and this method associated with additional energy costs. In addition, for the formation of the magnetic field construction made of permanent ring magnets [Bespalov et al. (1979)], placed outside of the tube volume of the diode, can be applied. However, this option increases the radial size of the pulse neutron generators.

In this paper the possibility of effective neutron generation in coaxial diode tube with laser-plasma source of deuteron on anode and outer hollow cylindrical cathode made from magnetic NdFeB compound material is shown. For such type of cathode the isolating magnetic field inductance is almost 2-3 times more than inductance created by outer magnets in secondary electrons emission region in case of their out of vacuum volume placement.

2. The experimental set-up

Scheme of the experimental set-up used to generate neutron in vacuum diode with laser-plasma deuteron source on anode, is shown in fig. 1. The residual pressure in the vacuum chamber (1) is about \( \approx 5 \times 10^{-2} \) Pa. High-voltage pulse sent to the anode (2) and the cathode (3) is earthed. The laser target (4) used in a form of TiD tablet was placed at the end face of the anode. For laser plasma generation we used the emission of a solid-state laser (5) with the wavelength of \( \lambda = 1.06 \) \( \mu \)m, power density is about \( q \approx 5 \times 10^{14} \) W/m\(^2\) and laser pulse duration \( \tau \approx 7 \) ns. The cathode made in a form of a hollow cylinder with the outer diameter of \( 8 \times 10^{-2} \) m, the inner diameter of \( 4.5 \times 10^{-2} \) m and \( 4 \times 10^{-2} \) m in height. The target for neutron generation, made from TiD or (CD\(_2\))\(_n\) was placed on inner surface of the cathode. Two types of materials were used during the cathode making: a permanent magnet NdFeB (neutron generation in the main mode) and an Al cathode (testing mode). Magnetic field inductance on the axis of the NdFeB cathode is about \( B \approx 0.4 \) T.

The high-voltage impulse generator (HVIG) was made according to Arcadyev-Marx scheme (7) from sections with \( C_0 = 4700 \) pF capacity and charge resistances \( R_0 = 16 \) k\( \Omega \). Charge voltage was \( U_0 = 15 \pm 18 \) kV. The number of sections varied in experiments from 10 up to 20 (\( n = 10 \div 20 \)) and had been chosen from \( U_5 = n \cdot U_0 \) condition, where \( U_5 \) is the total charge voltage HVIG, that is equal to output pulse amplitude in the idle mode. The maximum value \( U_5 \approx 350 \) kV was achieved with \( n = 20 \). For HVIG and laser deuteron source synchronization the scheme was used, where the laser beam part (up to 25% of intense) was for the arrester (8) running in the HVIG first section.

![Fig. 1. The experimental set-up scheme.](image-url)
Current and accelerating voltage was controlled on the diode gap with «Rogovskiy belt» (current transformer mode) and the balanced capacitance divisor respectively. The accelerating voltage amplitude was estimated by standard method with the use of spherical arrester and the discharge voltage table [Beyer et al. (1989)]. Laser pulse was registered by the coaxial photocell FEK-22 SPU. Neutron output was measured by the Long Counter of Hansen – McKibben with a thermal neutron detector and a cylindrical moderator made of polyethylene.

3. Electrical measurements

The characteristic waveforms of accelerating voltage $U(t)$ and diode current $I(t)$ on the diode gap, corresponding to magnetic electron isolation and $U_S \approx 300$ kV are shown in fig. 2. The delay between laser pulse and accelerating voltage pulse was chosen equal to 100-200 ns. Voltage pulse duration is defined by aperiodic equivalent capacitance HVIG discharge process with $C_{eq} = C_0/\hbar = 235$ pF (time constant $\tau_1 = R_0 C_0 = 75$ μs).

It is well-shown, that the time constant is more than current pulse duration $\tau_u \approx 0.2$ μs. However, the discharge rate of equivalent capacitance for the time period of running current rises dramatically and is determined by the time constant $\tau_2 = R_d \cdot C_{eq}$, where $R_d$ is the equivalent active capacitance of the diode gap ($R_d << R_0$). This leads to the decrease of accelerating voltage on the diode gap in comparison with the $U_S$ value.

Our experiments gave us the results, in which accelerating voltage amplitude decreases to $U_{AN} = 0.5 U_S$ without magnetic field (A1 cathode), and the achieving current in discharge equal to $I_N \approx 600$ A. With magnetic field influence (NdFeB cathode) accelerating voltage amplitude is higher and equal to $U_{AN} = 0.8 U_S$. However, the maximum achieving current diminishes to $I_d \approx 150$ A by the electronic conductivity suppression. These results confirm effective operation of magnetic isolation.

![Image](image_url)

Fig. 2. The characteristic waveforms of accelerating voltage $U(t)$ and diode current $I(t)$ on the diode gap (lower beam - laser pulse; line scanning is 0.25 ms/div).

The equivalent scheme of discharge circuit composed of equivalent capacitance $C_{eq}$, equivalent inductance $L_{eq}$ and resistance $R_d$ was considered. Current evaluations were made from suggestion, that the maximum value of $I_{max}$ is achieved in aperiodic mode, which is close to critical, i.e. $R_d \approx R_C$, where $R_C = 2 (L_{eq}/C_{eq})^{1/2}$ is the resistance of discharge circuit. It is easy to define $L_{eq}$ value from current oscillation period $T = 2 \pi (L_{eq}/C_{eq})^{1/2}$, measured in the short circuit mode. In our results $T = 0.22$ μs. Then $L_{eq} \approx 5$ μH and $R_C \approx 300$ Ω. In view of [Bessonov (1996)] for initial conditions $U(0) \approx 300$ kV and $I(0) = 0$, find that $I_{max} = 0.73 [U(0)/R_C] = 730$ A. This value $I_{max}$ is reached in $t = 2 (L_{eq}/RC) \approx 30$ ns after the beginning of the discharge, that is clearly shown on the current oscillogram (fig. 2).
4. Neutron measurements

Research of the neutron output in total solid angle per pulse $Q_{dd}$ was made by the neutron-generating target, made from TiD with the use of nuclear reaction D(d, n)$^3$He for two regimes: with magnet NdFeB cathode and A1 cathode. Maximum neutron output $Q_{dd}$ exceeded $10^7$ neutron/pulse. The results of measurements are shown in fig. 3.

![Fig. 3. Dependence of neutron output $Q_{dd}$ per pulse from $n\cdot U_0$ – total charging HVIG voltage: 1 – magnet NdFeB cathode; 2 – cathode from aluminum alloy DT 16.](image)

Except the marked neutron output increase $Q_{dd}$ with growth of total charging voltage, the considerable difference between acceleration modes with and without magnetic field is clearly observed. This also indicates the efficiency of magnetic isolation of electrons in accelerating gap (without magnetic field electron current is increased, so accelerating voltage is decreased).

5. Conclusion and discussion

The experiments with accelerating voltage values $U_A \leq 280$ kV, have shown the possibility of effective deuterons acceleration in diode with laser-plasma deuteron source and magnetic electron current isolation. With power density of laser emission about $q \approx 5\times10^{14}$ W/m² (energy 0.1 J) deuteron flows with current value $\geq 100$ A are obtained. We are planning to increase accelerating voltage amplitude up to 500 kV, laser pulse energy to 1 J, neutron pulse repetition rate to 10 Hz. In this case, as it shown in respective evaluations, the common neutron flow in total solid angle can reach $\approx 5\times10^9$ neutron/s.

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References


